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POWER SUPPLY FOR LEDS

The technical field of this disclosure is power supplies, particularly, a power supply for LEDs.

Significant advances have been made in the technology of white light emitting diodes (LEDs). White light LEDs are commercially available which generate 10-15 lumens/watt. This is comparable to the performance of incandescent bulbs. In addition, LEDs offer other advantages such as longer operating life, shock/vibration resistance and design flexibility because of their small size. As a result, white light LEDs are replacing traditional incandescent sources for illumination applications such as signage, accenting, and pathway lighting. The white LEDs can be used alone or in conjunction with colored LEDs for a particular effect.

The electrical characteristics of LEDs are such that small changes in the voltage applied to the LED lamp will cause appreciable current changes. In addition, ambient temperature changes will also result in LED current changes by changing the forward drop across the LEDs. Furthermore, the lumen output of LEDs depends on the LED current. The existing electrical power supplies for LED light sources are not designed to precisely regulate the LED current to prevent luminous intensity variations due to input ac voltage variations and ambient temperature. Operation of LED lamps at excessive forward current for a long period can cause unacceptable luminous intensity variations and even catastrophic failure. In addition, current electrical power supplies do not minimize power consumption to maximize energy savings.

It would be desirable to have a power supply for LEDs that would overcome the above disadvantages.

One form of the present invention is a power supply for a LED light source that comprises a power converter and a LED control switch. The power converter operates to provide a regulated power including a LED current and a LED voltage. The LED control switch further operates to control a flow of the LED current through the LED light source. The LED control switch further operates to clamp a peak of the LED current during an initial loading stage of the LED light source. This prevents damage to the LED light source due to a field misapplication.

A second form of the present invention is a power supply for a LED light source further comprising a detection circuit operating to provide a detection signal indicative of an operating condition of the LED light source associated with the LED voltage. The detection signal has a first level representative of a load condition of the LED light source. The detection signal has a second level representative of a short condition or an open condition indicative of the LED light source.

A third form of the present invention is a power supply for a LED light source further comprising a LED current sensor or a LED voltage sensor. Each sensor includes a differential amplifier and means for adjusting a gain of the differential amplifier.

The foregoing forms as well as other forms, features and advantages of the present invention will become further apparent from the following detailed description of the presently preferred embodiments, read in conjunction with the accompanying drawings. The detailed description and drawings are merely illustrative of the present invention rather than limiting, the scope of the present invention being defined by the appended claims and equivalents thereof.

FIG. 1 illustrates a block diagram of a power supply for an LED light source in accordance with the present invention;

FIG. 2 illustrates a schematic diagram of one embodiment of the **FIG. 1** power supply in accordance with the present invention;

FIG. 3 illustrates a timing diagram of one embodiment of a control circuit in accordance with the present invention;

FIG. 4 illustrates a schematic diagram of one embodiment of a short/open detection circuit in accordance with the present invention; and

FIG. 5 illustrates a schematic diagram of one embodiment of a differential amplification circuit in accordance with the present invention.

FIG. 1 illustrates a block diagram of a power supply **20** for powering an LED light source **10** including a variable number of LEDs wired in series and/or in parallel. A single-phase ac input **21** of power supply **20** provides a voltage $\mathbf{V_{AC}}$ to an AC/DC converter **22** of power supply **20** whereby AC/DC converter **22** converts voltage $\mathbf{V_{AC}}$ into a voltage $\mathbf{V_{DC}}$. AC/DC converter **22** provides voltage $\mathbf{V_{DC}}$ to a power converter **23** of power supply **20** whereby power converter **23** generates a regulated power $\mathbf{P_{REG}}$ including a LED current and a LED voltage $\mathbf{V_{LED}}$.

Power converter **23** provides regulated power $\mathbf{P_{REG}}$ to LED light source **10**. In operation, LED control switch **24** controls a flow of the LED current through the LED light source **10**. A LED current sensor **25** of power supply **20** provides a sensed current $\mathbf{I_{SE}}$ indicative of a magnitude of the LED current flowing through LED light source **10**. A LED voltage sensor **26** of power supply **20** provides a sensed voltage $\mathbf{V_{SE}}$ indicative of a magnitude of the LED voltage $\mathbf{V_{LED}}$ applied to LED light source **10**. Sensed current $\mathbf{I_{SE}}$ and sensed voltage $\mathbf{V_{SE}}$ are fed to a feedback controller **27** of power supply **20**. A signal reference **28** of power supply **20** provides a reference signal **REF** to a feedback controller **27**, whereby feedback controller **27** provides a feedback signal **FB** to power converter **23** based on sensed current $\mathbf{I_{SE}}$, sensed voltage $\mathbf{V_{SE}}$ and reference signal **REF**.

LED control switch **24** further operates to clamp a peak of LED current flowing through LED light source **10** to thereby protect the LED light source **10** from electrical damage. LED control switch **24** is particularly useful when LED light source **10** transitions from an open operating state to a load operating state (i.e., an initial loading), such as, for example, a connection of LED light source **10** to power supply **20** subsequent to an energizing of power supply **20**. An LED dimmer **29** of power supply **20** operates to control a desired dimming of LED light source **10** by providing a control signal **CS** to LED control switch **24**. Control signal **CS** can be in one of many conventional forms, such as, for example, a pulse width modulation signal ("PWM").

A short/open detection circuit **30** provides a detection signal **DS** as an indication of a short condition or an open condition of LED light source **10** based on the LED voltage $\mathbf{V_{LED}}$ applied to LED light source **10**.

The configuration of each component **21-30** of power supply **20** is without limit. Additionally, coupling among the components **21-30** of power supply **20** can be achieved in numerous ways (e.g., electrically, optically, acoustically, and/or magnetically). The number of embodiments of power supply **20** is therefore essentially limitless.

FIG. 2 illustrates a schematic diagram of one embodiment **120** of power supply **20** **(FIG. 1)** for one embodiment **110** of LED light source **10 (FIG. 1)** made in accordance with the present invention. Power supply **120** employs a flyback transformer with current feedback through a power factor corrector ("PFC") IC to supply power to LED light source **110**. To this end, power supply **120** includes an EMI filter **121**, an AC/DC converter ("AC/DC") **122**, a transformer **123**, a power factor corrector **124**, a feedback controller **125**, an optocoupler **126**, a LED control switch **127**, a LED PWM dimmer **129**, resistors **R1-R7**, capacitors **C1-C5**, diodes **D1-D3**, zener diodes **Z1-Z3** and a MOSFET **Q1** as illustrated in **FIG. 2**.

Voltage is supplied to power supply **120** at V_{IN} to EMI filter **121**. The voltage can be an ac input and is typically 50/60 Hertz at **120/230** V_{RMS}. EMI filter **121** blocks electromagnetic interference on the input. AC/DC **122** can be a bridge rectifier and converts the ac output of EMI filter **120** to dc. Transformer **123** includes a primary winding **W1, W4** and **W5**, and a plurality of secondary windings **W2** and **W3**. The windings **W1/W2** constitute the flyback transformer to power the LED light source **110**. The flyback transformer is controlled by PFC **124**, which is a power factor corrector integrated circuit, such as model L6561 manufactured by ST Microelectronics, Inc.

The flyback transformer transfers power to LED light source **110** where the LED current and the LED voltage are controlled by feedback control. The forward converter operation of windings **W1/W3** charge a capacitor **C3** and a reference current signal is generated between a series resistor **R4** and a zener **Z2**. The peak voltage across capacitor **C3** depends on the **W1/W3** turns ratio. The output dc voltage from flyback operation of windings **W1/W2** cannot be used to generate the reference current signal since the output dc voltage across LED light source **110** can have a wide range - from 2.6 Volts dc for one LED lamp to about 32 Volts dc for 8 LEDs in series. The forward converter operation of windings **W1/W3** can be used instead. The forward converter operation of the **W1/W5** windings can also be used to supply power to the integrated circuits, such as PFC **124**.

A sensed LED current I_{SE} flows through resistor **R1**, which is in series with the LED light source **110** via LED control switch **127**. A voltage representative of sensed LED current I_{SE} is applied to a non-inverting input of a comparator **U1**. A sensed LED voltage V_{SE} is generated by zener diode **Z1**. Sensed LED current I_{SE} and sensed LED voltage V_{SE} as well as a voltage reference V_{REF} are fed to feedback controller **125**, whereby a voltage feedback V_{FB} from feedback controller **125** drives an optocoupler **126** via resistor **R7**. In generating voltage feedback V_{FB}, feedback controller **125** employs a pair of comparators **U1** and **U2**, resistors **R8-R12**, and a capacitor **C6** as illustrated in **FIG. 2**.

Feedback controller **125** is necessary since optocouplers have a wide range of current transfer ratio (CTR). Feedback controller **125** maintains an accurate voltage feedback V_{FB} to thereby avoid large errors in LED current flowing through LED light source **110**. Optocoupler **126** isolates the dc circuit supplying the LED light source **110** from the ac circuit power supply at EMI filter **120**, the two circuits being on the opposite sides of the transformer **123**.

The output of the optocoupler **126** is connected to PFC **124**, which supplies a gate drive signal to MOSFET **Q1**. Control of MOSFET **Q1** adjusts the current flow through winding **W1** of transformer **123** to match the LED light source **110** power demand. The internal 2.5 V reference signal and an internal compensation circuit of PFC **124** maintains the voltage drop across a resistor **R6** at 2.5V. Although this example uses MOSFET **Q1** for adjusting the transformer current, alternate embodiments can use other types of transistors to adjust the current, such as an insulated gate bipolar transistor ("IGBT") or a bipolar transistor. The input to PFC **124** at Z_{CD} provides a reset signal powered from windings **W2/W4**.

Zener diode **Z1** also provides overvoltage protection for LED light source **110**. Specifically, zener diode **Z1** connects across the output connection to the LED light source **110** and clamps the output voltage to a specified maximum value. The nominal zener operating voltage is selected to be just over the maximum specified output voltage. In case of an output open circuit, the flyback operation of windings **W1/W2** of transformer **123** would continue to build the output voltage. The increasing output voltage turns on the zener diode **Z1** to thereby increase the amount of feedback to resistor **R6** from feedback controller **125** via resistor **R7** and optocoupler **126**. This limits the gate drive signal to MOSFET **Q1**, preventing the flyback converter from building the output voltage to the LED light source

110 beyond a specified maximum voltage. Similarly, zener diode **Z3** connected from the reset winding **W4** to resistor **R6** will prevent output overvoltage due to a malfunction of feedback controller **125**. In alternate embodiments, either zener diode **Z1** or zener diode **Z3**, or both zener diode **Z1** and zener diode **Z3** can be omitted depending on the degree of control protection required for a particular application.

LED control switch **127** includes a switch **SW1** in the form of a MOSFET and a switch **SW2** in the form of a bipolar transistor. Switches **SW1** and **SW2** can be in other conventional forms, such as, for example, an IGBT. As illustrated, a drain of MOSFET switch **SW1** is connected to LED light source **110**. A gate of MOSFET switch **SW1** is connected to a collector of bipolar switch **SW2**. A source of MOSFET switch **SW1** and a base of bipolar switch **SW2** are connected to zener diode **Z1**, resistor **R1**, and feedback controller **125**. An emitter of bipolar switch **SW2** is connected to ground. In operation, switch **SW1** is turned on and switch **SW2** is turned off when the LED current is below the desired peak. This mode permits a normal operation of the front-end components of power supply **120**. Conversely, switch **SW1** is turned off and switch **SW2** is turned on when the LED current exceeds the desired peak. This limits the peak of the LED current to a safe level whereby damage to LED light source **110** is prevented. As will be appreciated by one having skill in the art, LED control switch **127** is particularly useful upon a connection of LED light source **110** to an energized power supply **120** whereby capacitor **C2** discharges stored energy to LED light source **110** with a current having a peak clamped to thereby prevent damage to LED light source **110**.

MOSFET switch **SW1** can be operated by a conventional gate driver (not shown) or by an illustrated LED PWM dimmer **128**.

LED PWM dimmer **128** provides a PWM signal (not shown) to MOSFET switch SW1 in response to an external dim command V_{DC}. LED PWM dimmer **128** adjusts the duty cycle of the PWM signal to thereby produce a desired light output from LED light source **110**. LED PWM dimmer **128** is particularly useful in producing a precise and temperature sensitive minimum dim level for LED light source **110**.

LED PWM dimmer **128** includes a diode **D4** and a diode **D5** connected to the gate of MOSFET switch **SW1**. A comparator **U3** of LED PWM dimmer **128** is in the form of an operational amplifier having an output connected to diode **D4** and a non-inverting input for receiving a dimming command V_{DC}. A conventional astable multivibrator circuit **129** of LED PWM dimmer **128** is connected to diode **D5**. A ramp generator of LED PWM dimmer **128** includes a resistor **R16** connected to diode **D5** and a gate of transistor **Q2** in the form of a MOSFET. Transistor **Q2** can be in other forms, such as, for example, an IGBT. The ramp generator further includes an operational amplifier **U4**. A resistor **R15**, a resistor **R17**, a drain of bipolar transistor **Q2**, a capacitor **C7**, and an inverting input of comparator **U3** are connected to a non-inverting input of operational amplifier **U4**. Resistor **R15** is further connected to an output of operational amplifier **U4**. A resistor **R13** is connected to the output and an inverting input of operational amplifier **U4**. A resistor **R14** is connected to the inverting input of operational amplifier **U4** and ground. The source of MOSFET transistor **Q2** and capacitor **C7** are connected to ground. Resistor **R17** is further connected to a DC voltage source.

In operation, LED PWM dimmer **128** achieves a precise and temperature insensitive minimum dim level for LED light source **110**. Specifically, astable multivibrator circuit **129** produces a minimum pulse width (e.g., $T_{ON, MIN}$ illustrated in **FIG. 3**). The duration of the minimum pulse width is a function of a resistance and capacitance of astable multivibrator circuit **129**. Thus, the minimum pulse width is accurate and temperature insensitive. The ramp generator produces a ramp signal (e.g., **RS** illustrated in **FIG. 3**), which is periodically reset by the minimum pulse width. The ramp signal is supplied to the inverting input of comparator **U3** whereby a comparison of the ramp signal and dim command V_{DC} yields a target pulse width at the output of comparator **U3** (e.g., T_{ON} illustrated in **FIG. 3**). The minimum pulse width and the target pulse width are combined to provide the PWM signal at the gate of MOSFET switch **SW1**. As such, the PWM signal consists of the target pulse width overlapping the minimum pulse width when the dim command V_{DC} exceeds or is equal to the ramp signal. Conversely, the PWM signal exclusively consists of the minimum pulse width when the ramp signal exceeds the voltage dim command V_{DC}.

In practice, a suitable range for voltage dim command V_{DC} is 0 to 10 volts.

SHORT/OPEN CIRCUIT DETECTION

FIG. 4 illustrates one embodiment of short/open detection circuit **130**. A LED voltage drop $\mathbf{V_{LD}}$ across the LED light source **110** applied between a node **N1** and a node **N2**, and an input voltage $\mathbf{V_{IN}}$ is applied between node **N2** and a common reference. The LED voltage drop $\mathbf{V_{LD}}$ approximates zero (0) volts when LED light source **110** (**FIG. 2**) is shorted, and approximates the LED voltage $\mathbf{V_{LED}}$ of regulated power $\mathbf{P_{REG}}$ (**FIG. 1**) when LED light source **110** is an open circuit. The input voltage $\mathbf{V_{IN}}$ is typically in the range of six (6) volts to sixteen (16) volts. A comparator **U3** in the form of an operational amplifier provides a detection signal $\mathbf{V_{DS}}$ at a high level to indicate a "LED outage" condition of LED light source **110** and at a low level to indicate a normal operation of LED light source **110**. The "LED outage" condition is either indicative of a short or open of LED light source **110**.

Input voltage $\mathbf{V_{IN}}$ in the illustrated embodiment is a dc voltage. A dc-dc type power converter can therefore be used to supply power to LED light source **110** (**FIG. 2**). In alternative embodiments, detection circuit **130** can be adapted for use in ac to dc type power converters.

An emitter of a transistor **Q3** in the form of a bipolar transistor, and a zener diode **Z4** are also connected to node **N1**. Transistor **Q3** can be in other conventional forms, such as, for example, an IGBT. A resistor **R18**, a resistor **R21**, and a resistor **R22** are also connected to node **N2**. A base of bipolar transistor **Q3** is connected to resistor **R18**. Zener diode **Z4**, a resistor **R20** and resistor **R21** are connected to an inverting input of comparator **U5**. A collector of bipolar transistor **Q3**, a diode **D6**, and a resistor **R19** are connected to a node **N3**. Resistor **R19** and resistor **R20** are further connected to the common reference. Diode **D6** and resistor **R22** are connected to a non-inverting input of comparator **U5**.

For a normal operation of LED light source **110**, the LED voltage drop $\mathbf{V_{LD}}$ is greater than the base-emitter junction voltage of transistor **Q3** whereby transistor **Q3** is on, diode **D6** is in a non-conductive state, and the voltage at the collector of transistor **Q3** exceeds the input voltage $\mathbf{V_{IN}}$. As a result, the input voltage $\mathbf{V_{IN}}$ is applied to the inverting input of comparator U3. The conducting voltage of zener diode **Z4** is chosen to be above the LED voltage drop $\mathbf{V_{LD}}$ and therefore zener diode **Z4** is in a non-conductive state. As a result, a voltage applied to the non-inverting input of comparator **U2** will equate the input voltage $\mathbf{V_{IN}}$ reduced by a voltage divider factor established by resistor **R20** and resistor **R21**. The output of comparator

U5 will be low (e.g., close to ground) since the voltage applied to the inverting input exceeds the voltage applied to the non-inverting input.

For an open array condition of LED light source **110**, the LED voltage drop $\mathbf{V_{LD}}$ approximates the LED voltage $\mathbf{V_{LED}}$ of regulated power $\mathbf{P_{REG}}$, which is chosen to be higher than the voltage of zener diode **Z4**. The LED voltage drop $\mathbf{V_{LD}}$ is greater than the base-emitter junction voltage of transistor **Q3** whereby transistor **Q3** is on and the voltage at the collector transistor **Q3** exceeds the input voltage $\mathbf{V_{IN}}$. As a result, the input voltage $\mathbf{V_{IN}}$ is applied to the inverting input of comparator **U3**. The conducting voltage of zener diode **Z4** is lower than the LED voltage drop $\mathbf{V_{LD}}$ and zener diode **Z4** is therefore in a conductive state. As a result, a voltage applied to the non-inverting input of comparator **U5** will equate a summation of the input voltage $\mathbf{V_{IN}}$ and the LED voltage drop $\mathbf{V_{LD}}$ minus the conducting voltage of diode **D6**. The output of comparator **U5** will be high (e.g., close to the input voltage $\mathbf{V_{IN}}$) since the voltage applied to the non-inverting input exceeds the voltage applied to the inverting input.

For a short array condition of LED light source **110**, the LED voltage drop $\mathbf{V_{LD}}$ approximates zero (0) volts. The LED voltage drop $\mathbf{V_{LD}}$ is therefore less than the base-emitter junction voltage of transistor **Q3** whereby transistor **Q3** is off, the voltage at the collector transistor is pulled down by resistor **R19** and diode **D6** is conducting. As a result, a voltage applied to the inverting input of comparator **U5** will equate the input voltage $\mathbf{V_{IN}}$ reduced by a voltage divider factor established by resistor **R19** and resistor **R22**. The conducting voltage of zener diode **Z4** exceeds the LED voltage drop $\mathbf{V_{LD}}$ and zener diode **Z4** is therefore in a non-conductive state. The output of comparator **U5** will be high (e.g., close to the input voltage $\mathbf{V_{IN}}$) since the voltage applied to the non-inverting input exceeds the voltage applied to the inverting input.

In an alternate embodiment, an additional zener diode or a voltage reference can be inserted in the emitter path of transistor **Q3** to detect a voltage level other than less that one base-emitter junction of transistor **Q3**.

FIG. 5 illustrates a differential amplification circuit having a voltage output V_O that can be employed in LED current sensor **25** (**FIG. 1**) or LED current sensor **26** (**FIG. 1**). A resistor **R23** and a resistor **R25** are connected to an offset voltage source V_{OFF}. Resistor **R25**, a resistor **R26**, and a resistor **R28** are connected to an inverting input of an operational amplifier **U6**. A resistor **R24** and a resistor **R27** are connected to a non-inverting input of operational amplifier **U6**. Resistor **R23** and resistor **R24** are connected. Resistor **R28** is further connected to an output of operational amplifier **U6**.

In operation, the voltages applied to the inputs of the operational amplifier **U6** are lower than the supply voltage V_{dd} irrespective of the size of resistor **R23**. In one embodiment, resistors **R25** and **R26** are chosen to apply half of the offset voltage V_{OFF} to the inverting input of operational amplifier **U6**, and resistors **R24** and **R27** are chosen to obtain a proper common mode rejection (e.g., resistor **R28** equaling a parallel combination of resistor **R26** and **R28**). As a result, the gain of operational amplifier **U6** can be adjusted as desired.

It is important to note that **FIGS. 2-5** illustrates specific applications and embodiments of the present invention, and is not intended to limit the scope of the present disclosure or claims to that which is presented therein. Upon reading the specification and reviewing the drawings hereof, it will become immediately obvious to those skilled in the art that myriad other embodiments of the present invention are possible, and that such embodiments are contemplated and fall within the scope of the presently claimed invention.

While the embodiments of the invention disclosed herein are presently considered to be preferred, various changes and modifications can be made without departing from the spirit and scope of the invention. The scope of the invention is indicated in the appended claims, and all changes that come within the meaning and range of equivalents are intended to be embraced therein.